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XV.

CONTRIBUTIONS FROM THE JEFFERSON PHYSICAL LABORATORY, HARVARD UNIVERSITY.

NEUTRALIZATION OF INDUCTION.

By John Trowbridge and Samuel Sheldon.

Presented May 28, 1889

The invention of the telephone drew attention to the extraordinary sensitiveness of Faraday's electrotonic state, and immediate attempts were made to construct induction balances, so called, which might serve for quantitative measurements. Thus we have Hughes's induction balance, which had its prototype in the balance described in Maxwell's "Electricity and Magnetism," Vol. II. § 636, due to Felici,* and which differs from Hughes's balance merely in the employment of a galvanometer instead of a telephone. By substituting the latter instrument, Hughes showed that great sensitiveness could be obtained, and even proposed to adopt an instrument for measuring minute amounts of impurities in coins arising from alloys.

The great difficulty, however, in the employment of Hughes's induction balance in quantitative work arises from the difficulty of getting a good minimum of tone in the telephone. The method that Hughes employed was, briefly, to employ four coils, — two in a circuit through which an alternating current or an interrupted current was passed, and two other coils placed contiguous to the coils which were in the interrupted circuit, but in another circuit. By interposing a telephone in the last mentioned circuit, and by properly placing the coils in this circuit with reference to those in the circuit through which the interrupted current was passed, a balance could be obtained, or an imperfect minimum of sound in the telephone, when the induction between the sets of coils was neutralized. In order to obtain a standard, Hughes employed a wedge of zinc, which was thrust between one of the coils in the interrupted circuit and one of the coils in the telephone circuit, in order that the mutual induction between these coils might balance that arising between the other two similarly placed coils when a coin or sheet of metal was placed between these last mentioned coils. Other devices have also been employed by various investigators who have endeavored to use the apparatus for quantitative measurement. Alexander Graham Bell employed a modification of Hughes's induction balance for the detection of the presence of a bullet in the human body. In the form employed by him, one coil, which was a closely wound flat copper band, was made to slide over a similar one by means of a screw, one coil being placed in the telephone circuit and the other in a circuit containing a current-breaker. The induction arising from a similar pair of coils moved over a mass of metal like a bullet could thus be neutralized by this sliding coil arrangement. In no form, however, of Hughes's induction apparatus can one obtain a satisfactory minimum of tone in the telephone. There is never absolute silence, and no two observers can obtain the same point at which the sound seems to be a minimum. The failure to obtain this minimum is thus a radical defect in the instrument. It is doubtless very sensitive, but it cannot be called a quantitative instrument.

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* Nuovo Cimento, vol. ix. p. 345, 1859.

To remedy this defect, A. Overbeck and J. Bergmann* substituted an electro-dynamometer for the telephone, and worked out a method of obtaining the resistances of metals when they are in the form of thin circular plates. The standard of comparison they employed was a thin layer of mercury between disks of glass in a cylindrical reservoir. Preliminary investigations had shown the authors that a certain relation existed between the thickness and specific resistance and coefficient of induction of metals in the form of thin disks, which were placed between the coils of the induction balance. In a subsequent paper,† A. Overbeck gives the mathematical theory of the induction balance, which in the main is Maxwell's theory of current sheets applied to Arago's disk.‡ In employing the instrument to measure the effect of change of temperature on induction in copper plates, or, in other words, temperature coefficients, in which we found that Messrs. Overbeck and Bergmann had anticipated us,§ we were led to adopt the following form of the instrument, which differed entirely from that of these authors. Four coils were employed, as in the Hughes form of instrument. One of the coils in the telephone circuit was fixed upon a horizontal axis which was at right angles to the axis of the coil. The coil could therefore be moved through all positions, from perfect parallelism to its neighboring coil in the interrupted circuit to a position at right angles to this coil. The horizontal axis was provided with an index arm which moved over a graduated circle. Calling θ the angle of inclination of the axis of the movable coil with the axis of the fixed coil in the interrupted circuit, and N the strength of the induction current in the movable coil, we have evidently, on the supposition that the strength of the alternating current remains constant,

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* Annalen der Physik, xxxi., 1887, p. 792.

† Ibid., p. 812.

‡ Maxwell's Electricity and Magnetism, vol. ii. § 668 *et seq.*

§ Annalen der Physik, xxxvi., 1889, p. 783.

$$N = \text{constant} \times \text{cosine } \theta.$$

When the axes of the coils are at right angles, cosine $\theta = 0$, and we should have silence in the telephone. Since adopting this arrangement we have discovered that Dr. Bowditch, of the Harvard Medical School,* has employed this arrangement of a movable coil placed in front of a fixed coil as a modification of Du Bois Reymond's apparatus for controlling induction currents so that they may be administered by known amounts for physiological purposes. In Du Bois Reymond's apparatus one induction coil was simply moved away from a fixed coil through which an interrupted current was passed, much in the same manner as the coils in Wiedemann's form of galvanometer are moved. Here no minimum could be obtained. In Dr. Bowditch's form of this apparatus, theoretically a minimum should be obtained, that is, when cosine $\theta = 0$, or when the axes of the coils were at right angles. An indication of an electrical current is obtained even when the axes of the coils are at right angles, on account of the windings of the coil not being perfectly at right angles to those of the stationary coil.

That no minimum should be obtained when the axes of the coils are at right angles, and when induction arises from all parts of the circuit, is evident upon an elementary consideration of the subject. We have to deal in this form of instrument with the mutual induction which arises between the fixed coil and the movable one, and also with the self-induction which arises between the spires of the movable coil in the telephone circuit. The mutual induction can be reduced theoretically to zero by placing the movable coil of the telephone circuit at right angles to the fixed coil. The self-induction can be estimated as follows. Taking Maxwell's discussion for the induction between parallel circuits of radii A and a, we have the coefficient of mutual induction,

$$M = \iint \frac{\cos e \, ds \, ds'}{r}.$$

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* Proc. Am. Acad., vol. xi. p. 281.

Projecting one circle upon the plane of the circle of greater radius, A, we have

$$M = \int_0^{2\pi} \int_0^{2\pi} \frac{Aa \cos(\phi - \phi')\, d\phi\, d\phi'}{\sqrt{A^2 + a^2 + b^2 - 2Aa\cos(\phi - \phi')}} .$$

Making b the distance between the planes of the circles $= 0$, we pass from the case of mutual induction to that of self-induction between two spires of a coil which may be considered approximately circular. The form of M adapted for calculation is then

$$M = 4\pi \sqrt{Aa} \left\{ \left(c - \frac{2}{c} \right) F + \frac{2}{c} E \right\},$$

where $c = \frac{2\sqrt{Aa}}{(A + a)}$, and F and E are complete elliptic integrals to modulus c.

If we make $A - a = D$, or $A = D + a$, in which D is the distance between the spires at which the self-induction becomes insensible, the most perfect minimum can be attained. We have found that copper wire of 2 mm. diameter, wound in a flat loose spiral, the spires of which from centre to centre of the wire are 4 mm. apart, gives no sensible self-induction for spirals of eight to ten spires. On turning a movable coil of this form so that its axis may be perpendicular to the axis of the fixed coil, a perfect minimum can be obtained. A slight movement to the right or left of this position is quickly made evident by the note of the interrupted circuit which is heard in the telephone. It is evident that, if four coils are employed, as in Hughes's form of induction balance, the two coils in the telephone circuit should be wound in the manner we have indicated, to avoid self-induction. On placing a plate of metal between one set of the coils of this balance, the movable coil no longer gives a minimum at the position where its axis is at right angles to that of the fixed coil, but at some point removed a few degrees from this. By placing a mirror upon the movable coil, and by observing its deflection with a telescope, a greater refinement of reading is possible.

This instrument in its modified form suggests the possibility of neutralizing induction upon telephone circuits. The extension of the various systems for transmitting power by electricity, especially the electric car system, has led to great disturbances in the telephone circuits. These disturbances are due both to leakage from the power circuit into the telephone circuit, since the earth is used partially by the electric power companies in their return circuits, and to actual induction. The best remedy for these disturbances is doubtless the adoption by either the power companies or the telephone companies of entire metallic circuits, in which the earth plays no part. If this is not possible, a system of neutralization for the inductive disturbances might be adopted as follows. Let a shunt circuit from the electric light wire or the wire carrying the current for motors be led into a station through which also passes the telephone wire. The resistance of this shunt or derived circuit can be made suitable for the purpose. In all cases it reduces the resistance of the main line, and is therefore not prejudicial. On this shunt can be arranged a fixed coil, and on a neighboring telephone wire a movable coil of no self-induction. Let this movable coil be placed in front of the fixed coil in the motor circuit, and let it be turned until the mutual induction between it and the fixed coil neutralizes the induction produced at all points along the telephone circuit. Each telephone wire would need its movable coil, and to every movable coil would correspond a fixed coil in the shunt of the motor circuit. The operator at the central station could adjust the movable coils until the disturbances arising from induction at various points along the line are neutralized.